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Inflows and Outflows in Nearby AGN from Integral Field Spectroscopy

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Abstract. I report recent results on the kinematics of the inner few hundred parsecs (pc) around nearby active galactic nuclei (AGN) at a sampling of a few pc to a few tens of pc, using optical and near-infrared (near-IR) integral field spectroscopy obtained with the Gemini telescopes. The stellar kinematics of the hosts — comprised mostly of spiral galaxies — are dominated by circular rotation in the plane of the galaxy. Inflows with velocities of $\sim 50\,\mathrm{km\,s^{-1}}$ have been observed along nuclear spiral arms in (optical) ionized gas emission for low-luminosity AGN and in (near-IR) molecular gas emission for higher-luminosity AGN. We have also observed gas rotating in the galaxy plane, sometimes in compact (few tens of pc) disks which may be fuelling the AGN. Outflows have been observed mostly in ionized gas emission from the narrow-line region, whose flux distributions and kinematics frequently correlate with radio flux distributions. Channel maps along the emission-line profiles reveal velocities as high as $\sim 600\,\mathrm{km\,s^{-1}}$. Mass outflow rates in ionized gas range from 10^{-2} to $10^{-3}\,M_\odot\,\mathrm{yr^{-1}}$ and are 10–100 times larger than the mass accretion rates to the AGN, supporting an origin for the bulk of the outflow in gas from the galaxy plane entrained by a nuclear jet or accretion disk wind.

Keywords. galaxies: active, galaxies: kinematics and dynamics, galaxies: nuclei

1. Introduction

In the present paradigm for nuclear activity in galaxies, the accretion of gas onto a nuclear supermassive black hole (SMBH) triggers mechanical and radiative feedback which influences the host galaxies and intergalactic media of galaxy clusters to which they belong. The importance of feedback has been recognized in models for co-evolution of galaxies and black holes (Hopkins et al. 2005; Di Matteo et al. 2005), and in solving the "cooling-flow problem" in galaxy clusters (Rafferty et al. 2006). On galaxy cluster scales, the "X-ray cavities" (McNamara et al. 2005; Fabian et al. 2006; Allen et al. 2006) are a signature of strong feedback from the SMBH of the massive central galaxy. On galactic scales, the most clear signature of feedback from active galactic nuclei (AGN) are outflows observed in radio (Morganti et al. 2005), optical (Storchi-Bergmann et al. 1992; Komossa et al. 2008), UV (Crenshaw & Kraemer 2007), and X-rays (Chelouche & Netzer 2005). The origin of these outflows seems to be radio jets and/or accretion disk winds (Elvis 2000), most probably produced by radiation pressure (Proga 2007; Kurosawa & Proga 2008).

Outflows are a consequence of mass accretion to the SMBH, which implies transfer of matter to the AGN. Nevertheless, while outflows are ubiquitous among AGN, inflows are seldom observed. In the present contribution, I report on a search for inflows in the inner tens to hundreds of pc around nearby AGN using integral field spectroscopy. While looking for inflows, we find also outflows and I will report on their properties as well.

2. Observations

We have used integral field spectroscopy (IFS) at the Gemini telescopes in order to map the gas kinematics in the inner ~ 300 pc around nearby AGN. The final product of the IFS observations are "datacubes", which have two spatial dimensions — allowing the extraction of images covering a range of wavelengths — and one spectral dimension — allowing the extraction of spectral information of each spatial element.

In the optical, we have used the Integral Field Unit of the Gemini Multi-Object Spectrograph (IFU-GMOS), which has a field-of-view of $3.''5 \times 5''$ in one-slit mode or $5'' \times 7''$ in two-slit mode at a sampling of $0.''2$ and angular resolution (dictated by the seeing) of $0.''6$, on average. The resolving power is $R \approx 3000$.

In the near-infrared (near-IR) we have used the Near-Infrared Integral Field Spectrograph (NIFS) together with the adaptative optics module ALTAIR (ALTtitude conjugate Adaptive optics for the InfraRed), which delivers an angular resolution of $\sim 0.''1$. The field-of-view is $3'' \times 3''$ at a sampling of $0.''04 \times 0.''1$ and the spectral resolution is $R \approx 5000$. We have also used the IFU of the Gemini Near-Infrared Spectrograph (GNIRS) with a field-of-view of $3'' \times 5''$, and resolving power of $R \approx 5900$ covering the J, H, and K bands.

3. Inflows

Nuclear spirals — on scales of hundred parsecs — are frequently observed around AGN in images obtained with the *Hubble Space Telescope (HST)* (Martini et al. 2003). Martini & Pogge (1999) have shown that these spirals are not self-gravitating and may be the channels through which matter is being transferred to the nucleus to feed the AGN. This interpretation is supported by models (Maciejewski 2004) and by results such as those from Prieto et al. (2005) for the galaxy NGC 1097 and from Simões Lopes et al. (2007) for a larger sample of galaxies. The latter authors have built "structure maps" using images obtained with the *HST* Wide-Field and Planetary Camera 2 (WFPC2) through the F606W filter of a sample of AGN and a matched sample of non-active galaxies. The structure maps revealed dusty nuclear spirals in all early-type AGN hosts, but in only $\sim 25\%$ of the non-AGN, indicating that these spirals are strongly linked to the nuclear activity and map the matter in its way to feed the SMBH at the nucleus. Although the correlation between the nuclear spirals and the nuclear activity is strong, it is based only on morphology. In order to check if there are indeed inflows along the nuclear spirals, we began a project to map such inflows using the Gemini integral field spectrographs.

3.1. *Optical Observations*

Inflows in NGC 1097 and NGC 6951. The GMOS-IFU was used to map the gas kinematics in the inner $7'' \times 15''$ of the LINER/Seyfert 1 galaxy NGC 1097 (Fathi et al. 2005), corresponding to the inner 500 pc × 1 kpc of the galaxy. We have fitted Gaussians to the Hα and [N II] λ6584 emission lines and find that the kinematics is dominated by rotation in the galaxy plane, but with non-circular motions superimposed. In order to isolate these motions, we fitted a circular rotating disk model to the velocity field and subtracted the model from the measured velocities. The residual velocity field was spatially correlated with a nuclear spiral structure, supporting previous suggestions (Prieto et al. 2005) that these spirals are indeed associated with inflows towards the nucleus. Further analysis of the gas kinematics in the nuclear region of NGC 1097 was recently published by Davies et al. (2009), confirming the inflows along the nuclear spirals. Similar results were obtained for another LINER galaxy, NGC 6951 (Storchi-Bergmann et al. 2007). The streaming motions along the nuclear spirals have velocities of $\sim 50\,\mathrm{km\,s^{-1}}$ and the estimated mass

inflow rate in ionized gas is $\sim 10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$. Coincidentally, this mass inflow rate is of the order of the mass accretion rate to the active nucleus — under the assumption that the AGN luminosity is extracted from the mass accretion rate in the prescription of a radiatively inneficient accretion flow, which seems to apply to such nuclei (Nemmen et al. 2006). The actual mass inflow in neutral and molecular gas is probably much larger than that in ionized gas estimated here.

Inflows in M 81. We have also mapped the gas kinematics in the inner $7'' \times 15''$ of the nearby LINER/Seyfert 1 galaxy M 81. Due to its proximity, the region covered at the galaxy is only $\sim 120\,\mathrm{pc} \times 250\,\mathrm{pc}$, at a spatial resolution of $\sim 10\,\mathrm{pc}$. At these small galactic scales, the gas velocity field does not show a clear rotation pattern, and we used a particular method to isolate non-circular motions: we obtained the stellar velocity field using the "penalized pixel fitting technique (pPXF)" of Capellari & Emsellem (2004), and subtracted the stellar velocity field from that of the gas. The results were blueshifts in the gas kinematics on the far side of the galaxy and redshifts on the near side, suggesting inflows along the galaxy minor axis. A further technique we are exploring is the use of principal component analysis (PCA) applied to the datacube. This method is described by Steiner et al. (2009) and by Steiner et al. in these proceedings. The result is the separation of the information in "eigen-spectra," which reveal spatial correlations and anti-correlations in the emission-line data. A preliminary result of the application of this technique to the inner $5'' \times 5''$ ($85 \times 85\,\mathrm{pc}^2$) of the M 81 datacube is illustrated in Figure 1, which shows a comparison between the kinematics derived from the datacube and that from a "reconstructed" datacube (Steiner et al. 2009) using only 3 eigen-spectra. The latter reveals what seems to be a compact rotating disk ($\sim 8\,\mathrm{pc}$ radius) around the nucleus. More results on M 81 are discussed by Schnorr Müller et al. in these proceedings.

3.2. *Near-Infrared Observations*

Inflows in NGC 4051. We have looked for inflows toward AGNs in the near-IR using NIFS with the adaptative optics module ALTAIR at the Gemini North Telescope. We have mapped the stellar and gas kinematics in the inner $\sim 100\,\mathrm{pc}$ of the Seyfert galaxy NGC 4051 from K-band spectra. Channel maps along the $\mathrm{H_2}\,\lambda 2.12\,\mu\mathrm{m}$ emission-line

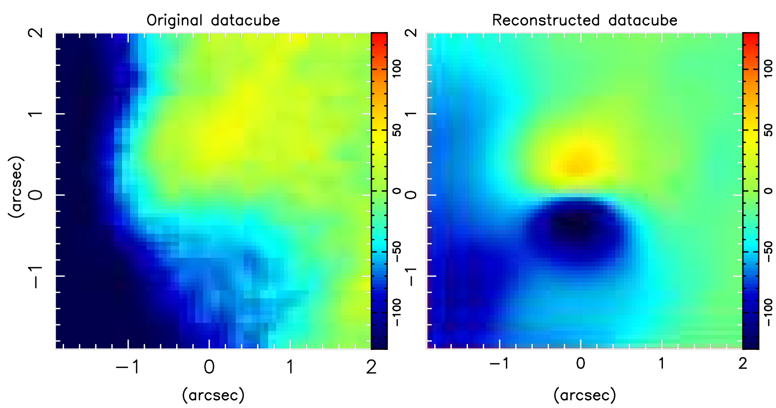

Figure 1. Left: Gas kinematics obtained from the centroid velocities of the [N II] λ6584 emission line in the datacube of M 81. Right: Gas kinematics obtained from the same velocticies measured in the reconstructed datacube after the PCA analysis, considering only the contribution of 3 eigen-spectra which reveal a compact ($\sim$8 pc radius) rotating disk around the nucleus. Velocities are color-coded as in the bar to the right, in units of $\mathrm{km\,s^{-1}}$.

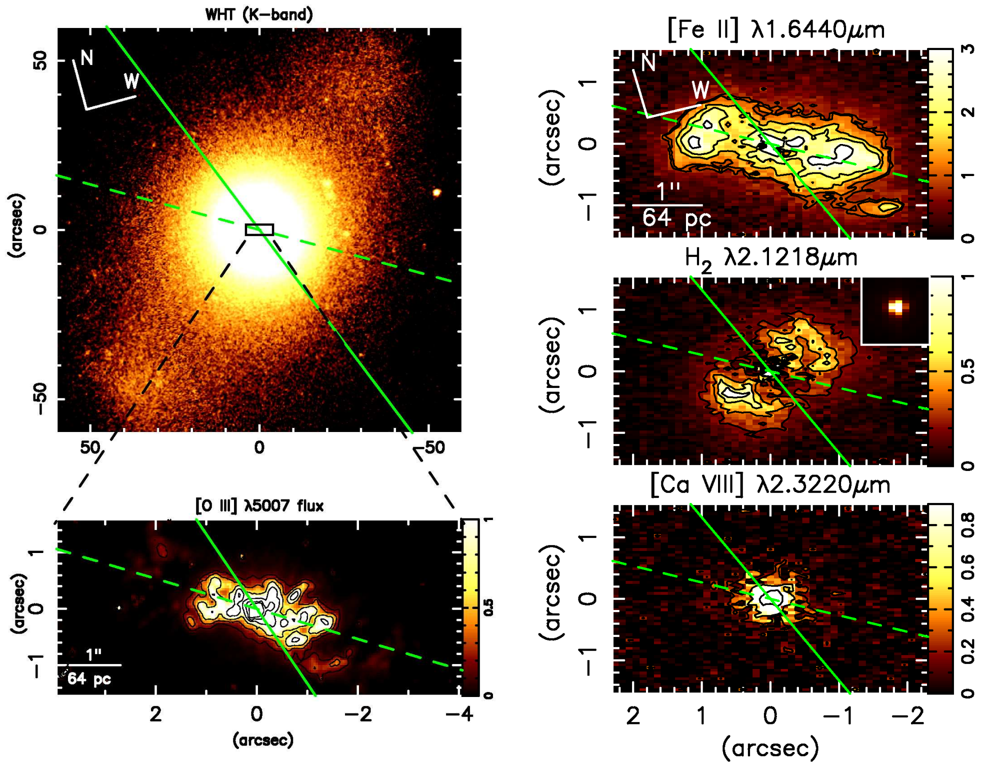

Figure 2. Left top: K-band image of the central region of NGC 4151 obtained with the William Herschel Telescope. The continuous line shows the orientation of the major axis of the galaxy, and the dashed line that of the NLR bi-cone. The rectangle shows the region covered by the NIFS observations. Left bottom: *HST* [O III] λ5007 narrow-band image of the NLR in the NIFS field-of-view. Right: Intensity maps in the inner 3×5 arcsec^2. Top: [Fe II] intensity map; middle: H_2 intensity map; bottom: a coronal line intensity map (Storchi-Bergmann et al. 2009).

profiles show blueshifts on the far side and redshifts on the near side of the galaxy along nuclear spirals which can be interpreted as inflows towards the nucleus if the gas is in the plane of the galaxy (Riffel et al. 2008).

Inflows in NGC 4151. We have also mapped the gas excitation and kinematics with NIFS in the inner $\sim 200\times500$ pc^2 of the Seyfert galaxy NGC 4151 at a spatial resolution of $\sim$8 pc (Storchi-Bergmann et al. 2009, 2010). We have found distinct flux distributions for the ionized, molecular, and coronal gas, as illustrated in Figure 2: while the ionized flux distributions follow the ionization bicone previously observed in the [O III] λ5007 emission line — which characterizes the narrow-line region (NLR) of this galaxy — the molecular gas avoids the bicone region, and the coronal gas emission is barely resolved.

Besides the flux distribution, the kinematics of the molecular and ionized gas is also distinct: the molecular gas shows only rotation, and is thus probably confined to the galactic plane, while the ionized gas shows both rotation and outflows. The ionized gas emission is not restricted to the bicone, where the dominant kinematics is outflow from the nucleus, but shows also emission from the galactic plane within $\sim$65 pc from the nucleus, where the gas kinematics is dominated by rotation (similarly to the molecular gas). Thus, although we could not map actual inflows in NGC 4151, the circumnuclear

gas rotating in the plane is probably the mass reservoir to feed the SMBH. In support to this idea, a previous study of the H I gas kinematics has found inflows along the large scale bar (Mundell et al. 1999), oriented approximately along the galaxy minor axis. This flow could have built the molecular gas reservoir we have obseved within a few tens of parsecs from the nucleus along the galaxy minor axis, which has a similar orientation to that of the large scale bar.

The NIFS observations of NGC 4151 have also revealed the presence of an unresolved red nuclear continuum, well reproduced by a black body with temperature $T = 1340\,\mathrm{K}$ (Riffel et al. 2009), and identified with the hottest part of the dusty torus postulated by the unified model of AGNs (Antonucci & Miller 1985). This torus may originate in inflows from the molecular gas reservoir described above.

Inflows in Mrk 1066. We have used NIFS to map also the stellar and gas kinematics in the inner $\sim 350\,\mathrm{pc}$ of the Seyfert 2 galaxy Mrk 1066, using J and K-band spectroscopy. Preliminary results for the stellar and molecular (H_2) gas velocity fields are shown in Figure 3. The blueshifts on the far side of the galaxy and redshifts on the near side observed in the H_2 residual map suggest inflows towards the center along nuclear spiral arms. These arms seem to feed a rotating disk with radius of $\sim 100\,\mathrm{pc}$ around the nucleus. Further results on the kinematics of the nuclear region of Mrk 1066 are discussed by Riffel et al. (these proceedings).

4. Outflows

4.1. *Optical Observations*

Outflows in NGC 2273, NGC 3227, NGC 4051 and NGC 3516. We have obtained data on the stellar and gaseous kinematics of the inner $\sim$400 pc of 6 Seyfert galaxies using the GMOS–IFU in the wavelength range $\sim 7500 - 9300$Å (Barbosa et al. 2009). The stellar kinematics was obtained using the calcium triplet at $\approx$8500Å and the gas kinematics using the [S III]λ9069Å emission line. The stellar kinematics is dominated by circular rotation in the galaxy plane. The gaseous kinematics shows also a rotational component, intepreted as due to gas rotating in the plane as the stars. In these four galaxies, the gas kinematics shows, in addition, blueshifts and redshifts due to outflows from the nucleus, whose velocities (derived from the centroids of the emission lines) reach $\sim 200\,\mathrm{km\,s^{-1}}$ at a

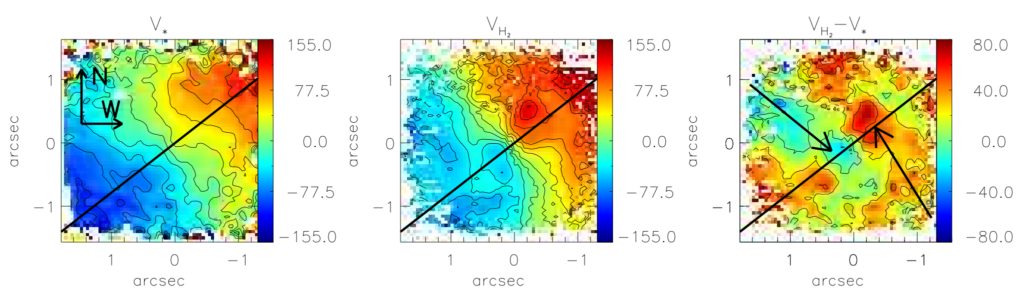

Figure 3. Kinematics of the inner $700 \times 700\,\mathrm{pc}^2$ of Mrk 1066. From left to right: stellar velocity field, molecular gas velocity field (from centroid of the $H_2\,\lambda\,2.1218\mu$m emission-line) and residual between the molecular and stellar velocity fields. Note the compact rotating disk in H_2 emission. The black line shows the line of nodes derived from the stellar kinematics, while the arrows show the spiral arms, which become noticeable only in the residual map. Velocities are color-coded as indicated in the bar to the right in units of $\mathrm{km\,s^{-1}}$.

few hundred parsecs from the nucleus. The outflows are spatially associated with the radio structure and both the radio flux maps and the [S III] flux and centroid velocity maps show discrete components (knots of emission), which we interprete as due to intermitent ejection of plasma which compresses the surrounding interstellar medium, driving the observed outflows. This interpretation is supported by the observation of an increase in the gas velocity dispersion in the regions surrounding the radio knots.

Channel maps along the [S III] emission line show that the the highest velocities are observed close to the nucleus, contrary to what is observed in the centroid velocity maps, which show the highest velocities away from the nucleus. We attribute this difference to the fact that the centroid velocity probes the brightest emission: in the vicinity of the nucleus the brightest component is the one originating in the galactic disk (with velocities close to systemic), while away from the nucleus the brightest component is the outflowing one. As a consequence, the centroid velocities show an apparent increase in velocity that mimics acceleration along the NLR. In the channel maps, we see high velocity gas in the nucleus, showing that the outflow does not leave the nucleus at zero velocity. We interpret this high velocity gas as an outflowing wind from the AGN or ambient gas more directly interacting with this wind. As this highest velocity gas moves away from the nucleus, it pushes and accelerates the gas from the disc.

We have estimated mass outflow rates in the range 10^{-3}–$10^{2}\,M_\odot\,\mathrm{yr}^{-1}$. These are approximately 10 times the accretion rates of their respective AGN, indicating that the bulk of the outflowing gas is entrained from the galaxy ISM (Veilleux et al. 2005). We have also estimated that the power of the outflow is about 10^{-4} times the bolometric luminosity.

4.2. *Near-Infrared Observations*

Outflows in NGC 4151. As discussed above, NIFS observations of NGC 4151 show that part of the ionized gas surrounding the nucleus is orbiting in the plane and may comprise

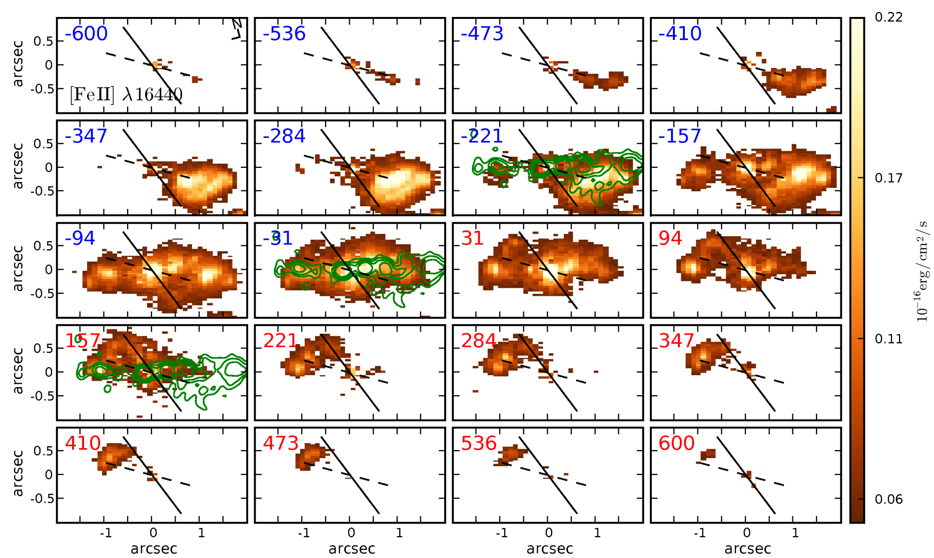

Figure 4. Channel maps obtained by integrating the flux within velocity bins of $63\,\mathrm{km\,s^{-1}}$ along the [Fe II] $\lambda 1.64\mu$m emission-line profile from the NLR of NGC 4151. The numbers in the upper left corner of each panel are the central velocity of the bin, in $\mathrm{km\,s^{-1}}$ relative to systemic. The continuous line shows the orientation of the galaxy major axis and the dashed line shows the orientation of the NLR bicone. Contours are from a radio MERLIN image.

the fuelling flow to the AGN. Part of the gas is also outflowing, with centroid velocities reaching up to $400\,\mathrm{km\,s^{-1}}$ away from the nucleus. Channel maps along the emission-line profiles reveal even higher velocities (up to $\sim 600\,\mathrm{km\,s^{-1}}$) which are observed close to the nucleus, as illustrated in Figure 4 (Storchi-Bergmann et al. 2010), and do not support acceleration along the NLR as suggested by previous authors.

The axis of the bicone observed in the optical and near-IR flux maps shows a distinct orientation from that of a nuclear radio jet. As the radio jet probably originates in the "funnel" of the accretion disk, the origin of the emitting gas cannot be the same. The biconical outflow probably originates from an accretion disk wind, and the distinct orientation suggests that the accretion disk is warped. The channel maps close to zero velocity (systemic velocity) show nevertheless some correlation between the emitting gas intensities and the radio knots, as can be observed in Figure 4. We interpret this correlation as due to interaction of the radio jet with gas from the galaxy plane, which is almost in the plane of the sky and thus have observed velocities close to zero. We estimated a mass outflow rate of $\sim 1 M_{\odot}\,\mathrm{yr^{-1}}$ along each cone, which exceeds the inferred black hole accretion rate to the AGN by a factor of $\sim$ 100. The kinetic power of the outflow as measured from the emission-line intensities and velocities is $\sim 3 \times 10^{-3}$ times the bolometric luminosity.

Outflows in ESO 428–G14, NGC 7582, Mrk 1066, Arp 102B, and SDSS J0210–0903. We have found a strong correlation of the ionized gas flux distributions and kinematics with the radio-flux distributions in the Seyfert galaxies ESO 428–G14 (Riffel et al. 2006) and Mrk 1066. Further results for the latter galaxy are discussed in the contribution by Riffel & Storchi-Bergmann (these proceedings). Outflows have been found also in the nuclear region of NGC 7582 (Riffel et al. 2009a). The radio galaxy Arp 102B shows an outflow correlated with the radio flux distribution (Couto, these proceedings), Finally, the gas kinematics of the post-starburst quasar SDSS J0210–0903 is discussed by Sanmartin, Storchi-Bergmann, & Brotherton (these proceedings).

5. Summary and Conclusions

I have discussed a number of studies of the gas kinematics in the inner few hundred parsecs around nearby AGN using integral field spectroscopy. These data have been used to search for gas inflows which feed the nuclear SMBH. In doing so, we also mapped outflows in ionized emitting gas which are more easily observable than inflows.

Inflows. In the optical, we were able to map inflows observed in ionized gas around the low-luminosity AGNs NGC 1097, NGC 6951, and M 81. In the first two galaxies, we found streaming motions towards the nucleus on scales of hundred parsecs along spiral arms. In the latter, we used PCA analysis to unveil a compact rotating disk with radius $\sim 8\,\mathrm{pc}$, which may be fuelling the AGN. In more luminous AGN, we were successful in finding similar kinematics in molecular gas emission in the near-IR. The H_2 gas kinematics reveal both streaming motions towards the nucleus and compact rotating disks. The mass inflow rates in ionized gas are of the order of the nuclear accretion rate (derived from the luminosity of the AGN), while those in molecular gas are much smaller. In both cases, we conclude that we are only seeing the "hot skin" (ionized/excited by the AGN) of a much more massive inflow of colder molecular and neutral gas. In the optical, we have also observed emission from ionized gas in rotation around the nucleus, and conclude that this gas may be part of the mass reservoir being used to feed the AGN.

Outflows. Outflows are observed mostly in ionized gas emission, and the centroid velocity maps usually show larger velocities — reaching typically 200–400 $\mathrm{km\,s^{-1}}$ — away from the nucleus (hundred of parsecs scales), suggesting acceleration along the NLR. Nevertheless, channel maps extracted along the emission-line profiles reveal high velocities (up to $\sim 600\,\mathrm{km\ s^{-1}}$) close to the nucleus and do not support acceleration. We suggest that the apparent acceleration observed in the centroid velocity maps is due to the fact that the brightest component — which is probed by these maps — is the disk emission near nucleus (which has low velocity) but is the outflow emission outwards (which has higher velocity). The mass outflow rates along the NLR are in the range $10^{-3} - 10^{-2}\,M_\odot\,\mathrm{yr}^{-1}$ which are 10 to 100 times the mass accretion rate to the SMBH. This result supports previous claims (e.g., Veilleux et al. 2005) that the origin of the NLR gas is entrainment of the galaxy ISM by a radio jet or accretion disk wind. We have estimated the kinetic power of the outflows as $\sim 10^{-4} - 10^{-5}$ times the bolometric luminosity.

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